

# Metrics for Anomalous Charging currents in Polymer Tantalum Capacitors

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**Abstract**—Anomalous charging currents (ACC) in polymer tantalum capacitors may appear as a temporary short circuit that can last for dozens of milliseconds, cause failures to the parts, or cause malfunctions to fast operating electronic systems. Currently, there is no standard technique or set of metrics to evaluate the level of ACC which compares results obtained by different users and manufacturers. In this work, ACC in different types of capacitors were characterized by analysis of current transients during the constant voltage ramp or power surge testing (PST) techniques. It is shown that although the shape of transients may vary at different test conditions, the transfer charge and energy remain practically the same. The level of ACC is characterized by the energy dissipated in the part during PST. Variations of the dissipated energy with moisture content, test temperature, and voltage are evaluated. Effects of different reflow soldering conditions and long-term (up to 3000 hours) storage at 125 °C are discussed.

**Keywords**— *polymer tantalum capacitor, testing, anomalous transient currents*

## I. INTRODUCTION

Anomalous transients after step voltage application in discharged and dry parts is a phenomenon peculiar to polymer tantalum capacitors (PTC). High level of transient currents that are especially significant during the first several or dozens of milliseconds after voltage application was first discovered by Y. Freeman and co-workers and named anomalous charging currents (ACC) [1]. The level of ACC can be in the range of amperes and can cause temporary shorts and malfunctions in some electronic systems. ACC may also substantially increase the time necessary to charge capacitors that is not acceptable for fast-acting circuits e.g., power supplies in solid state drives (SSD).

The phenomenon manifests also as increased capacitance, dissipation factor, and leakage currents that are time and voltage dependent and can rise at lower temperatures [2]. Although the nature of ACC is not fully understood, it is most likely related to the Schottky emission of charge carriers over the barrier at the conductive polymer/Ta<sub>2</sub>O<sub>5</sub> dielectric interface. Rising of the barrier with time that results in reduction of currents was explained by the orientation of polymer dipoles [1, 3] or by electron trapping processes and specifics of the structure of conductive polymers [2].

Since first discovered in 2013, all later investigations of ACC [4, 5] confirm that the phenomenon is specific for dry PTCs only, the level of ACC increases with voltage, and decreases at high temperatures. Manufacturers of PTCs are trying to reduce the level of ACC by modification to conductive polymers and improvements to the technology and processes of the oxide formation [3, 6]. However, the absence of a standard testing technique and metrics for ACC characterization impedes the progress in development of new types of capacitors and acceptable use of PTCs in hi-rel systems or space applications.

The purpose of this work is to demonstrate that the power surge testing (PST) and the energy dissipated during the transients can be used to characterize the level of ACC. This metric was used to assess various factors affecting anomalous transients in PTCs including voltage, temperature, preconditioning, reflow soldering, and long-term high temperature storage.

## II. TECHNIQUES FOR ANALYSIS OF ACC

ACC can be revealed by monitoring current and voltage transients after step voltage application from a source measure unit (SMU). These variations depend on the dynamic characteristics of the SMU and set-up conditions. Two methods of charging can be used: a linear increase of voltage and an instantaneous (within less than a millisecond) rise of voltage to the rated level (VR).

### A. Constant voltage ramp (CVR) technique

The CVR technique was used in several publications [3, 5, 7] where the level of ACC was characterized by currents exceeding the displacement currents in the parts. Typical *I-V* characteristics at different ramp rates in comparison with the relevant displacement currents are shown in Fig.1. This technique revealed high anomalous transient currents, but even at high current levels (amperes), these currents did not cause catastrophic failure to the parts.

At low voltages, the measured current is limited by the displacement current,  $I_{displ} = C \times dV/dt$ , and remains relatively constant. Increasing currents at higher voltages are due to anomalous charging, so the level of ACC can be characterized by the ratio of the current measured at the rated voltage,  $I_{ACC}(VR)$  to  $I_{displ}$ .

To compare test results for different types of capacitors, the currents were normalized to the value of capacitance. Variations of the normalized values of  $I_{ACC}(VR)$  and  $I_{displ}$  with the ramp rate are shown in Fig.2. Depending on the part type,  $I_{ACC}$  varies with the ramp rate faster or slower than  $I_{displ}$ , so in general, there is no optimal rate to get maximum ratio of  $I_{ACC}$  and  $I_{displ}$ .

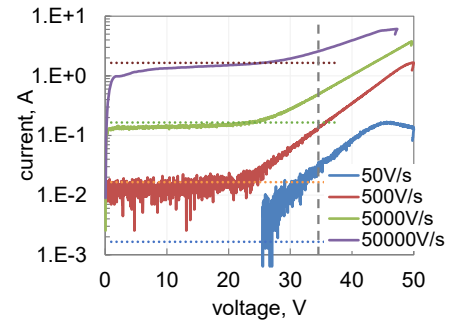


Fig.1. *I-V* characteristics in a 33 µF 35 V polymer tantalum capacitors at different ramp rates. Dotted lines indicate displacement currents, and the dashed line corresponds to the rated voltage.

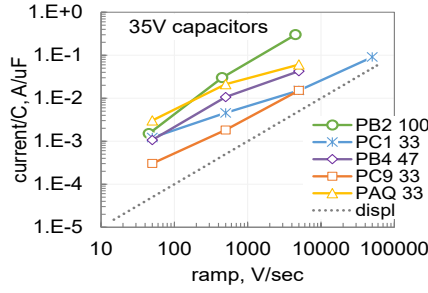


Fig.2. Variations of displacement and charging currents normalized to capacitance with the ramp rate for different types of 35 V PTCs. The currents in amperes are normalized to the value of capacitance in  $\mu\text{F}$ . The legend indicates the part type and the value of capacitance in  $\mu\text{F}$ .

### B. Power Surge Test

During PST, a capacitor is stressed by a voltage pulse with an amplitude corresponding to the rated voltage, VR, while the current is recorded with time. Because ACC can be revealed after the displacement current spike that continues typically less than 1 msec, the power supply should be capable of stabilizing voltage within 1 msec. In this study, an advanced high-speed dynamic SMU power system N7973A, available from Keysight, was used to generate power on/off cycles (typically 200 msec) at currents limited from 0.3 A up to 30 A and voltages up to 60 V. This SMU is capable of stabilizing voltages within 0.3 msec even at currents exceeding 30 A.

Examples of PST for different types of capacitors are shown in Fig.3. In some cases, at relatively low levels of ACC, as for PC8 capacitors, the currents smoothly decrease with time. At relatively large levels, current relaxation curves may have humps as shown for PC1 and PC3 capacitors.

The charge transferred in the process of anomalous transients,  $Q_t$ , and the dissipated energy,  $U_d$ , were calculated by digital integration of the recorded currents and voltages:  $Q_t = \int (I_i \times \Delta t)$ , and  $U_d = \int (I_i \times V_i \times \Delta t)$ .

If the voltage across a capacitor remains constant, the energy can be calculated as  $U_d = Q_t \times VR$ . When the current is limited by the SMU, the output voltage may be below VR as shown in Fig. 5a, so in general  $U_d \leq Q_t \times VR$ .

To determine  $U_d$  using PST, the integration was carried out up to the moment when the current decreased to below 0.01 A, and for the CVR technique up to the moment when the voltage reached VR. Calculations of  $U_d$  for CVR testing that were made at different ramp rates were compared with the data obtained during PST. Results of these calculations for six types of capacitors are shown in Fig.4. In all cases, the dissipated energy less decreased with the ramp rate, and was at least two times less than during PST.

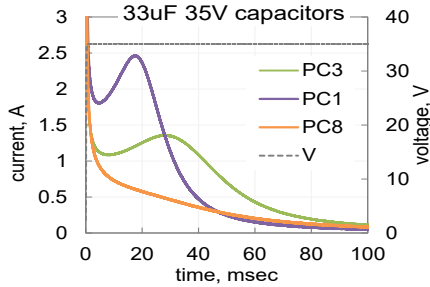


Fig.3. Variations of currents and voltages in three types of 33  $\mu\text{F}$  35 V polymer tantalum capacitors during PST.

Due to a short duration of the energy pulse, testing results in adiabatic heating of the tantalum slug that could cause

significant thermo-mechanical stresses. For this reason, assessment of the severity of ACC is recommended by the dissipated energy. Due to a higher level of  $U_d$  during PST compared to CVR testing, contrary to CVR testing in some cases, PST resulted in catastrophic failures of the parts.

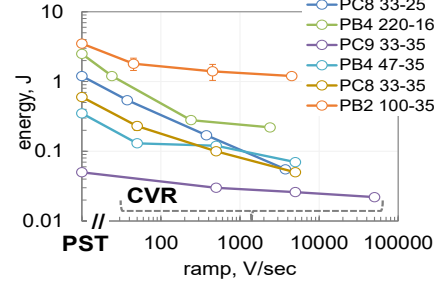


Fig.4. Variations of energy dissipated during CVR testing at different ramp rates in comparison with PST for six types of capacitors. The legend indicates part types. The numbers before dash correspond to capacitance in  $\mu\text{F}$  and after the dash to the rated voltage.

### III. METRICS SELECTION

Testing of various tantalum capacitors at different PST conditions showed that the duration of ACC increases at reduced limiting currents. An example PST for 220  $\mu\text{F}$  10 V capacitors at different SMU currents is shown in Fig.5a.

The values of  $Q_t$  and  $U_d$  were calculated for different types of capacitors during PST at limiting currents varying from 0.3 to 30 A. Results of these calculations (see Fig.5b) show that the charge and energy vary less than 10% even when the current increases tenfold. It is possible that due to initially low barrier at the interface conductive polymer/Ta2O5, injection of charge carriers remains high until a certain charge is trapped and accumulated in the system. The trapping processes are likely similar to those that are responsible for the resistive switching memory effect in PEDOT:PSS polymers [8]. For practical purposes, it is important that the transfer charge and dissipated energy do not change significantly with the shape of current relaxation curves. This allows values of  $Q_t$  and  $U_d$  to be used as a metrics for ACC. Considering that the dissipated energy is directly related to the level of stress in the slug, this parameter is preferred for characterization of anomalous transients.

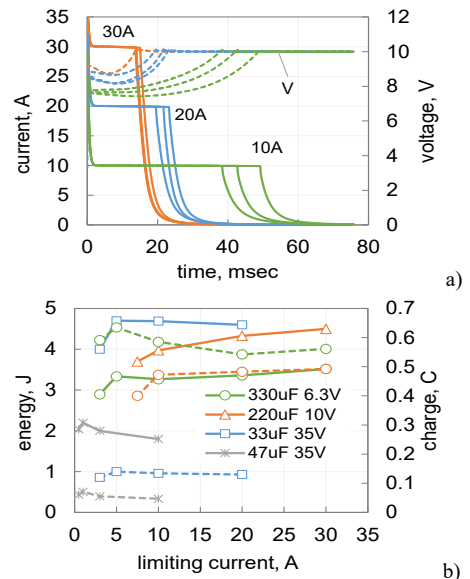


Fig.5. Transients in three samples of 220  $\mu\text{F}$  10 V capacitors at different limiting currents (a) and variations of  $Q_t$  (dashed lines) and  $U_d$  (solid lines) in different types of capacitors during PST with the level of limiting current (b).

Experiments with different lots of PTCs allow for grading of the severity of ACC. This level can be characterized as high for parts with  $U_d \geq 1$  J, as low for parts with  $U_d < 0.1$  J, and as medium in other cases. The spread of data between different samples in a lot varies from 7 to 30%.

#### IV. FACTORS AFFECTING DISSIPATED ENERGY

Factors affecting ACC that were analyzed in this study include preconditioning, temperature, voltage, soldering, and long-term storage at high temperatures.

##### A. Preconditioning

Previous studies indicated that moisture absorbed in capacitors substantially suppressed the level of ACC [1, 5, 7]. However, the effect of the amount of moisture has not been studied. In this study, to saturate the parts with moisture, parts were stored in a humidity chamber at 85 °C and 85% RH for one week. Baking for 16 to 24 hours at 125 °C was used to assure dry conditions of the slug. Respectively, capacitors were labeled wet or dry depending on preconditioning.

To evaluate the sensitivity of ACC to moisture content, two lots of 100  $\mu$ F 35 V polymer capacitors were tested at wet and dry conditions, and then with time of storage at room environment (20 °C and 40% RH) for four weeks. Results of these measurements are shown in Fig.6. Drying increased  $U_d$  in both lots by almost two orders of magnitude. Storing at room conditions, even for 3 hours, reduced  $U_d$  by approximately 30%. After four weeks,  $U_d$  was practically at the level of wet capacitors.

The data indicate that even a relatively small amount of moisture, less than 10% of the amount absorbed at room condition, can change ACC significantly and reduce it to the level of wet capacitors after long-term (~ 1 month) storage at room conditions. For this reason, it is critical to specify that PST measurements should be taken within no more than 3 hours after the bake.

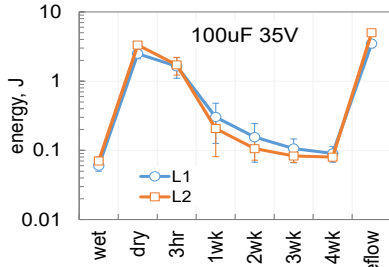


Fig.6. Variations of the dissipated energy in two lots of 100  $\mu$ F 35 V capacitors at different preconditioning and during storage at room environments.

##### B. Temperature

To assess the effect of temperature, PST was carried out for five types of capacitors in the range of temperatures from -55 to +125 °C. Results of these tests are shown in Fig. 7. To avoid reduction of currents caused by repeat measurements, different groups of capacitors (3 to 5 samples in a group) were used for testing at different temperatures.

In all cases,  $U_d(T)$  curves had a maximum, that depending on the part type varied, between -40 °C and +20 °C. The maximum energy was in the range from 6 J down to less than 0.1 J. At temperatures below or above  $T_{max}$ , the energy decreased from several times to orders of magnitude. In most cases,  $U_d$  at temperatures above 85 °C was close to or below 0.1 J. These results are consistent with data reported in

literature and suggest that ACC will have negligible effect for parts operating at high temperatures.

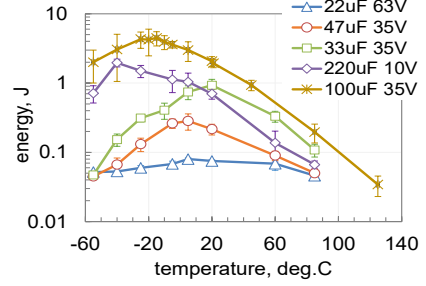


Fig.7. Temperature variations of the dissipated energy during power surge testing of 5 types of capacitors.

##### C. Voltage

Results of PST at room temperature for 6 types of capacitors tested at voltages from 0.5VR to 1.25VR are shown in Fig. 8. The dissipated energy did not change significantly when the voltage increased from VR to 1.25VR. However, reduction of voltages from VR to 0.5VR decreased  $U_d$  more than two orders of magnitude which agrees with earlier studies [5, 7]. These results confirm a significant effect of voltage on the level of ACC and indicate the efficiency of the voltage derating for ACC reduction.

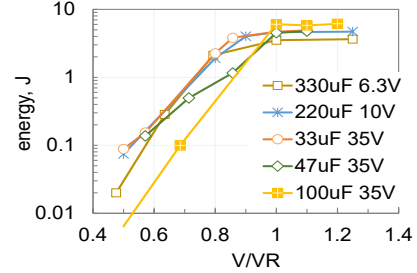


Fig.8. Effect of voltage on the dissipated energy during PST for six types of capacitors.

##### D. Reflow soldering

Increasing ACC after reflow soldering has been previously reported [3] and is expected considering the reduction of moisture level after exposing capacitors to high temperatures. Analysis shows that even at relatively low temperatures used for Sn/Pb eutectic reflow soldering (235 °C), this process decreases moisture content in capacitors by 50% to 75% [9]. However, there is still a lack of information about the effect of preconditioning before soldering on the level of ACC.

Two lots of 220  $\mu$ F 16 V capacitors with 5 samples in a group were used for this study. PST was carried out before and after one and three cycles of reflow soldering simulation at conditions specified in J-STD-020: preheating for 100 sec at 150 °C or 200 °C and exposure to 235 °C for 20 sec. The parts were preconditioned either by bake at 125 °C for 20 hours (dry capacitors) or by storage for one week at 85 °C 85%RH (wet capacitors).

Results of these tests are displayed in Fig.9 and show that the parts not only had different levels of ACC after wet and dry preconditioning, but their response to reflow stresses depended on the initial moisture content. Contrary to expectations, the level of ACC in the initially wet capacitors increased more than in initially dry parts. Increasing the number of reflow cycles to three raises  $U_d$  even for the initially dry capacitors, but the effect is more significant for wet parts. After three reflow cycles, the dissipated energy in the initially wet capacitors was approximately 80% greater

compared to dry parts. A substantial increase of failures caused by reflow soldering of wet PTCs compared to dry parts was observed in [10]. It is possible that one of the reasons for these failures was a significant increase in the dissipated energy during the first power-on cycle caused by a high level of ACC.

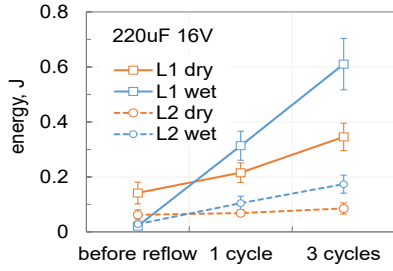


Fig.9. Effect of reflow soldering on two lots of 220  $\mu$ F 16 V capacitors preconditioned by 20-hour baking at 125  $^{\circ}$ C (dry) and 1 week storage at 85  $^{\circ}$ C 85% RH (wet).

The dissipated energy in initially dry capacitors increases almost two times after 3 cycles of reflow soldering. However, capacitance measurements showed that the amount of moisture in the slugs remained practically the same. Obviously, the amount of moisture remaining after reflowing simulations in the initially wet parts is not less than in the dry capacitors, but the level of ACC increased substantially for wet parts. These results indicate that the level of moisture is not the only factor affecting ACC. Another possible reason is increasing of the crystallinity in conductive polymers after exposure to high temperatures [11]. The relevant structural variations may change in concentration and the state of electron traps thus, altering ACC processes.

#### E. Long-term storage at 125 $^{\circ}$ C

Variations of the dissipated energy in the process of high-temperature storage (HTS) at 125  $^{\circ}$ C are shown for three types of PTCs in Fig.10a and for six more types in Fig.10b. Results show that the energy might increase up to 3 orders of magnitude during first 100-200 hours and remain practically the same for thousands of hours afterwards. This means the parts that have a relatively low level of ACC, below 0.1 J, will not degrade further during long-term aging at high temperatures.

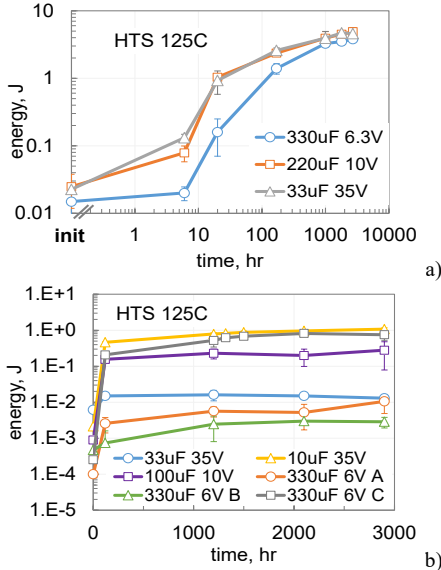


Fig.10. Effect of storage at 125  $^{\circ}$ C on results of PST for three (a) and six more (b) types of capacitors. Letters A, B, and C in figure (b) corresponds to different types of 330  $\mu$ F 6.3 V capacitors.

Note, that a 24-hour bake typically used to dry-out tantalum capacitors [9] might be not sufficient to reach the maximum level of ACC.

#### V. CONCLUSION

The transfer charge and energy dissipated during anomalous transients do not depend on the shape of the currents' relaxation and can be used to characterize anomalous transients in polymer tantalum capacitors during PST.

Using PST and dissipated energy as a metric allowed to reveal several factors affecting ACC:

1. The level of ACC reduces noticeably by relatively small amount of moisture that can be absorbed even after 3 hours of storage at room conditions.
2. Different part types have maximum ACC between -40  $^{\circ}$ C and +20  $^{\circ}$ C, and the dissipated energy became negligibly small at temperatures above 85  $^{\circ}$ C.
3.  $U_d$  decreases exponentially at voltages below VR.
4.  $U_d$  may increase more than two orders of magnitude during the first 100-200 hours at 125  $^{\circ}$ C but remains stable up to 3000 hours of storage.
5. Reflow soldering may substantially increase the level of ACC, especially for parts with initially high level of absorbed moisture.

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